Motion estimated and compensated compressive sensing dynamic MRI under field inhomogeneity

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Introduction: Recently, we proposed a compressed sensing dynamic MR technique called k-t FOCUSS that extends the conventional k-t BLAST/SNESE by exploiting the sparsity of x-f signal. Especially, we found that when a fully sampled reference frame is available more sophisticated prediction methods such as RIGR and motion estimation and compensation (ME/MC) can significantly sparsify the residual and improve the overall reconstruction quality. Among these, ME/MC is especially useful since it can be used for arbitrary trajectories such as radial and spiral. However, our extensive experiments with non-cartesian trajectory have demonstrated that there exist technical issues in applying the ME/MC to non-cartesian trajectory due to the field inhomogeneities. This paper showed that if the ME/MC is done in magnitude image domain and the lost phase is compensated from the current frame estimate, the field inhomogeneity problem can be significantly alleviated. Furthermore, we showed that the introduction of half-pel ME/MC and intra block mode within the estimation loop can improve the overall reconstruction quality of compressed sensing dynamic MRI.

Theory: In k-t FOCUSS [1], the unknown image ρ is calculated by iteratively solving following Eq. (1).

$$\rho = \rho_0 + \Theta_n F^H (F\Theta_n F^H + \lambda I)^{-1}(v - F^*\rho_0) \qquad \text{where} \quad \Theta_n = W_n W_n^H . \tag{1}$$

Here, v, W_n, F, and ρ_0 represent the k-t measurements, continuously updated weighting matrix, sparsifying transform, and prediction term, respectively. The main advantage of k-t FOCUSS over k-t BLAST is that the weighting matrix W is continuously updated using the x-f image estimate. This weighing matrix updates guarantees the optimality of k-t FOCUSS in a compressive sensing perspective [1]. To achieve improved performance, it is better to estimate the term ρ_0 more accurately since it makes the residual signal much sparser. One of the interesting scheme toward this goal is motion estimation and compensation (ME/MC) used in video compression. In ME/MC for k-t FOCUSS, the reference frame does not need to be temporally continuous with current dynamic frames, and can be separately obtained from dynamic acquisition. However, it is interesting to note that unlike the video compression full resolution current frame is not available at the encoder. Hence, in k-t FOCUSS[2], the initial estimate of the current frames are obtained without ME/MC, and then ME/MC is applied consecutively using the refined current frame as shown in Fig.1. This makes the residual sparse, and we can apply additional k-t FOCUSS update effectively for the remaining residual signal. However, in applying k-t FOCUSS for non-cartesian trajectories, we found that the ME/MC does not often effectively sparsify the residual around the blood flow changes as illustrated in Fig.2 (a). We found that this is mainly due to the field inhomogeneities which results in phase changes. In order to alleviate this problem, the present work shows that ME should calculates motion vector d_m for each block B_m by minimizing the cost function in Eq.(2),

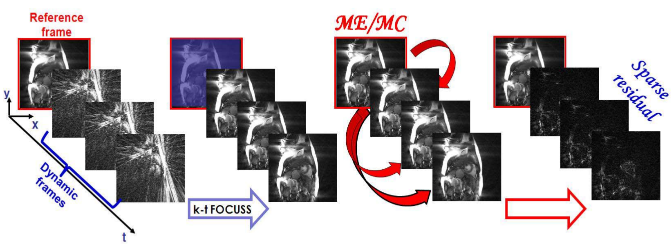

Fig. 1. k-t FOCUSS with ME/MC [2].

$$E(d_m) = \sum_{x \in B_m} \| \sigma_{ref}(x + d_m) | - | \sigma'_{cur}(x,t) \| \tag{2}$$

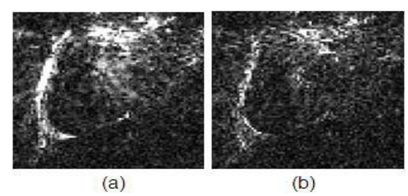

Fig. 2. The residual error of ME/MC using (a)complex value and (b) absolute value.

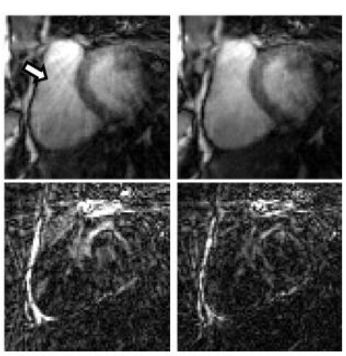

Fig. 3. SW k-t FOCUSS

where σ_{ref} and σ'_{cur} represent reference frame and estimated current dynamic frame by k-t FOCUSS. Note that the ME is done in magntitude domain rather than using complex images. It turns out that the main origin of the artifact in Fig.2(a) comes from the motion estimation using complex values reference and current frames, which are susceptible to field inhomogeneity artifact. After the estimation of motion vectors, the motion compensation should be done to compensate the lost phase information. This can be done readily using the phase compensation term θ obtained at first k-t FOCUSS reconstruction as following:

$$\sigma_{MC}(x,t) = | \sigma_{ref}(x + d_m) | e^{i\theta(x,t)} . \tag{3}$$

The modified ME/MC can significantly sparsify the residual signal as shown in Fig.2(b). With the proposed phase correction, additional high level ME/MC schemes often used in video compression can be easily incorporated. In this paper, we also employ the half-pel ME/MC and intra block mode. In half-pel ME/MC, the motion vector is estimated up to subpixel accuracy by interpolating the reference frames. In intra block mode, the some of the blocks are not motion compensated if the absolution difference is significantly great than the threshold. We found that the half-pel and intra block mode can improve the robustness of our k-t FOCUSS algorithm.

Result: To evaluate the performance of our algorithm, we compared the results of k-t FOCUSS with sliding window in Fig.3. The results were reconstructed from 12 radial lines. While sliding window result shows streaking artifacts as indicated by white arrow, k-t FOCUSS with ME/MC effectively removes the streaking artifacts.

Discussion & Conclusion: In non-cartesian trajectory, due to the field inhomogeneities, we found that ME/MC should be done using absolute values and the phase should be corrected later using the current estimate. This field inhomogeneity correction scheme in ME/MC for k-t FOCUSS can significantly improved performance. Furthermore, more sophisticated ME/MC scheme using half-pel and intramode can be incorporate effectively.

References: [1] H. Jung et al. Physic. Med. Biol. vol 52, pp. 3201-3226, June, 2007 [2] H. Jung et al, Magn. Reson. Med, to appear 2008